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A New Modelling of Crack Propagation with Fatigue-Creep-Oxidation Interaction under Non Isothermal Loading

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This paper deals with the extension of a crack growth model to high temperature complex loading and application to turbine disc. The proposed model is based on an extensive experimental study performed by SNECMA Moteurs on N18 from 450°C to 650°C, in isothermal and also in non isothermal condition, which comprises fatigue with or without hold times and special sequence tests representative to the disc in service. The crack growth model is built up in the framework of classical linear elastic fracture mechanics. Time effects at high temperature are traduced by creep-fatigue and oxidation-fatigue interactions. The proposed writing in non isothermal condition is very attractive for easy model identification on a large temperature domain. Model predictions are shown for a large set of experimental data including complex loading in non isothermal condition.

1 INTRODUCTION

This paper presents a phenomenological model able to simulate the crack growth in a metallic material at high temperature and under complex cyclic loading condition. This one uses the actual stress intensity factor as the loading variable, but also several material parameters are introduced in order to describe the history of the various processes that operate near the crack tip during for instance an hold period at high temperature: the mechanical stress redistribution due to visco-plasticity, the creep damage process under tensile condition, the environmental driven brittle oxide at crap tip that increases the fatigue crack propagation and the interaction of overloads with both fatigue and creep crack growth.

After reminding and discussing the main features of the model, originally proposed by Prigent [1] and Kruch et al [2], we propose in a first section a model extension to account for non isothermal complex loading together with the functions describing the fatigue, creep and oxidation damages and the different interactions. We give then in the second section the results of the application made with N18 aeronautical superalloy, the model predictions of many isothermal tests performed at different temperatures and also of non isothermal tests more representative of real loading subjected to the component in service.

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2 CRACK GROWTH MODEL

2.1 Assumptions of the creep-fatigue-oxidation interaction under complex loading

The proposed model is built up in the framework of classical linear elastic fracture mechanics. The main points the model must take into account are: the fatigue crack propagation, the creep crack propagation, the stress intensity factor relaxation during creep, the creep-fatigue interaction and the environment effects. The various state variables that store the post-loading events are as follows:

- A threshold K_s^f for fatigue crack growth, similar to the opening stress intensity factor. Its evolution is influenced both, by fatigue overloads (and under-loads) as proposed by Baudin and Robert [3], and by the hold time or low loading rate during which a relaxation can occur. Built up in the basis of Onera's crack propagation model proposed to account for complex loading in fatigue, it can take into account the overload effects applied during a cycle through the plastic zone evolution in front of the crack and the value of the fatigue threshold K_s^f ; that will not be developed in this paper.
- This threshold is also introduced to describe the creep crack growth K_s^c in a time dependent expression.
- The size of the oxidised zone at the crack tip l_p, from which is deduced an effective local toughness of the material K_C, that operates in the fatigue crack growth model through a Forman's expression.

To account for the creep-fatigue contribution for a given cycle, the crack growth is classically divided into two parts, the first one concerning the fatigue propagation, and the second one the creep:

$$da = \left(\frac{da}{dN}\right)_{Fatigue} dN + \left(\frac{da}{dt}\right)_{Creep} dt \qquad (1)$$

For the treatment of a general complex loading, for instance with hold time and overload as described in figure 1, we post the fatigue crack growth (the minimum value of the stress intensity factor is memorised) for the given loading at the next unloading. Only time dependent phenomena such as creep crack growth, threshold relaxation and oxidised zone increasing are computed during the loading. Let us precise that the threshold is supposed to be constant during the creep crack growth. It is only actualised just before to post the fatigue crack growth, and just after for instance to take into account an overload (or an under-load). The environment effects are also posted for the next cycle through decreasing of the material toughness.

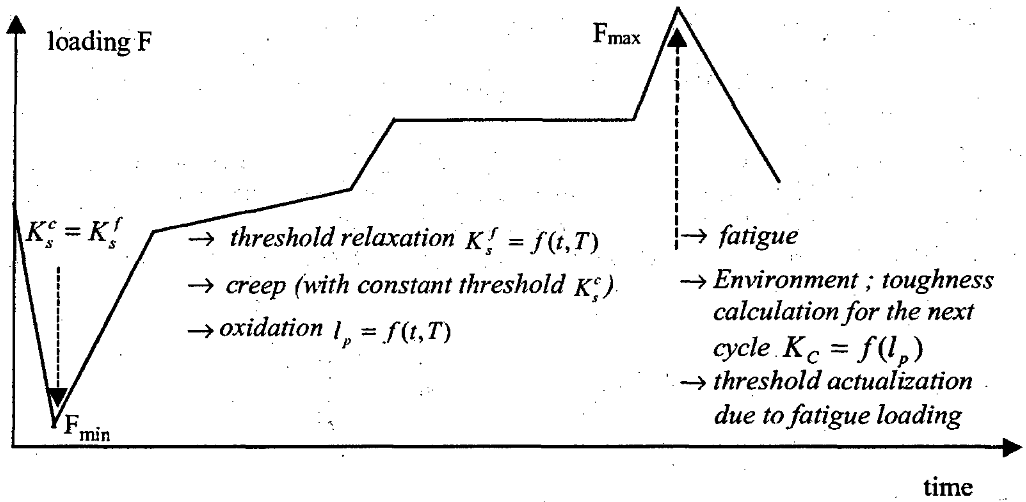

FIGURE 1. General scheme of the creep-fatigue-oxidation interaction model

2.2 Non isothermal writing

Let us consider a thermo-mechanical loading for which the temperature $T(t)$ can strongly vary during the force cycle $F(t)$ or the stress intensity factor $K(t)$ at the instant t. The difficulty for the model extension in non isothermal condition concerns the fatigue law which predicts a fatigue damage rate per cycle. Which temperature do we have to consider ? We can consider the maximum temperature over the cycle to be in the security way, or to define a mean temperature T^* as proposed by Taïra (4).

The way we propose here to account for the temperature dependency is to use a reduced stress $S = \dfrac{K(t)}{K_{cv}(T(t))}$ as parameter describing the thermo-mechanical fatigue cycle, where $K_{cv}(T)$ is the material toughness (without oxidation effect) which is temperature dependent, the fatigue law can then be supposed temperature independent. In another words, this hypothesis requires that the fatigue material properties evolve with temperature only through the evolution of the material toughness supposed here to obey to an Arrhenius law:

$$K_{cv}(T) = K_{cv}^o \exp(\frac{Q}{RT}) \qquad (2)$$

where Q (the activation energy) and K_{cv}^o are material coefficients. We define then a fatigue law as a Forman [5] expression of S variable:

$$\left(\frac{da}{dN}\right)_{Fatigue} = \frac{C_f^*\left[S_M - S_s^{f*}\right]^{\eta_f^*}}{(1-R)\left[S_c - S_M\right]} \qquad (3)$$

where C_f^* and η_f^* are temperature independent material coefficients. S_s^{f*} is the fatigue threshold, also temperature independent. R is the loading ratio, S_c the normalised toughness equal to 1 without environment effect, and S_M the maximum value of S during the cycle. From tests results obtained in fatigue regime, without time effect such as creep or environment effect, and for several temperatures, we have to find only one mistress curve if we report $\left(\dfrac{da}{dN}\right)$ as a function of $\Delta S = \dfrac{K_M}{K_{cv}(T(t))} - \dfrac{K_s^f}{K_{cv}(T(t))}$.

Tests performed by Bernede [6] on Astroloy superalloy in vacuum and in air at high temperature show a great influence of environment on the crack propagation process. The main environment effect is the material oxidation at the crack tip leading to a reduction of the mechanical properties. It is introduced in the model through the variation of the local normalised toughness induced by oxidation:

$$S_{c1}(t) = \frac{K^o_{cox}}{K^o_{cv}}\left[1-u+u.\exp\left(\frac{mz^*}{l_p(t)}\right)\right] \qquad (4)$$
$$S_c = Min(S_{c1},1)$$

where mz^* and u are material temperature independent coefficients. By considering the toughness $K_{cox}(T)$ of the completely embrittled material at the crack tip, necessarily lower than $K_{cv}(T)$ and also supposed to obey to the same Arrhenius law (same activation energy):

$$K_{cox}(T) = K^o_{cox}\exp(\frac{Q}{RT}) \qquad (5)$$

we assume then that the ratio $\dfrac{K^o_{cox}}{K^o_{cv}}$ is temperature independent. $l_p(t)$ is the penetration length of oxide inside the material as a function of time and temperature:

$$dl_p(t) = \frac{1}{4}(F(x)\alpha)^4 l_p^{-3}dt$$
$$\alpha = \alpha_o \exp(\frac{-Q_o}{RT}) \qquad (6)$$

α_o and the activation energy Q_o are material coefficients. This function traduces the material oxidation kinetics at the crack tip [7] and its temperature dependency. The function $F(x)$ accounts for the loading effect on the oxidation kinetics, for instance an hold time after an overload. x is the ratio between the actual load and the previous overload:

$$F(x) = cx^4 = c(\frac{F(t)}{F_M})^4 \qquad (7)$$

c is a constant. In the case of increasing load, x equals to 1 and the oxidation effect on fatigue process is completely operative.

As creep damage is concerned, the extension in non isothermal does not require supplementary development because the creep model is described by a temporal equation:

$$da = \int_{t_1}^{t_2} C_c(T(t))\left[K(t)-K_s^c\right]^{\eta_c(T(t))}dt \qquad (8)$$

A given cycle (time, load, temperature) is treated by considering time steps sufficiently small to assure the calculation convergence, and by taking at each time step the corresponding parameters $C_c(T(t))$ and $\eta_c(T(t))$. Crack propagation by creep is posted as soon as the actual stress intensity factor $K(t)$ is higher than the non propagation threshold K_s^c. We can remind here that this threshold is considered as a constant during the cycle and equals to the fatigue non propagation threshold K_s^f calculated at the previous cycle. On the other hand, we compute during creep the relaxation of this one, by a relaxation type equation deduced from the study of viscous behaviour of the material:

$$d\left(\frac{K_s^f}{K(t)}\right) = -A(T(t))\left(\frac{K_s^f}{K(t)}\right)^{\omega(T(t))} dt \qquad (9)$$

As well as the creep model integration, we consider the instantaneous values of the parameters $A(T(t))$ and $\omega(T(t))$ at each time step of the calculation.

3 APPLICATION TO A NICKEL-BASE SUPERALLOY FOR TURBINE DISK

We present in this section the application made on N18 Nickel-base superalloy at high temperature. A wide experimental program has been conducted by SNECMA Moteurs [8] from 450°C to 650°C for various loading conditions. After showing the results of the identification, we give predictions of many isothermal and non isothermal tests.

3.1 Identification of the model parameters

The proposed formulation makes the model attractive for its identification on a large temperature domain. As a matter of fact, the fatigue law evolves with temperature through the variation of the material toughness $K_{cv}(T)$ supposed to be known. Fatigue tests results performed at high temperature but at high loading frequency in a pure fatigue regime, for which time effects such as creep and oxidation can be neglected, or at low temperature whatever the loading frequency (no time effect), are then used to identify the fatigue coefficients.

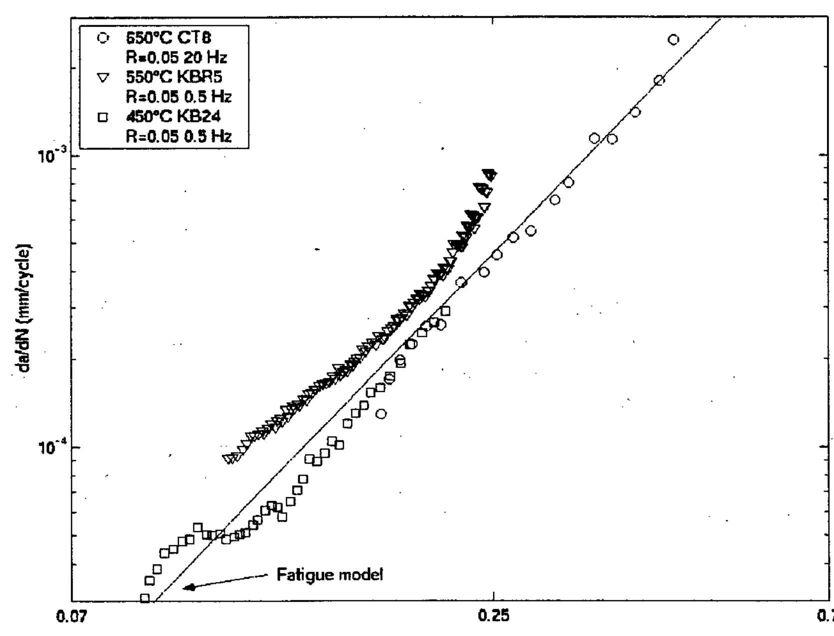

FIGURE 2. Identification of the pure fatigue model

The figure 2 gives the result of C_f^* and η_f^* identification (the initial non propagation threshold S_s^{f*} is taken equal to $0{,}5$) by reporting in a diagram ($\frac{da}{dN}, \Delta S$) tests results obtained at 450°C (we observed any time effect at this temperature), 550°C (we suppose to have a small time effect for those tests performed at 0,5 Hz) and 650°C (at 20 Hz in a pure fatigue regime) for the same loading ratio. At a given temperature, we can then calculate $C_f(T)$ and $K_s^f(T)$ parameters by the following relations:

$$\begin{aligned} C_f(T) &= C_f^* \cdot K_{cv}^{1-\eta_f^*}(T) \\ K_s^f(T) &= S_s^{f*} \cdot K_{cv}(T) \end{aligned} \tag{10}$$

Pure creep tests at different temperatures are required to identify the creep model temperature dependent parameters $C_c(T)$ and $\eta_c(T)$ of equation 8. The initial non propagation threshold $\frac{K_s^c}{K_{max}}$ is also taken equal to $0{,}5$. We reported in figure 3 the results of the identification at 650°C.

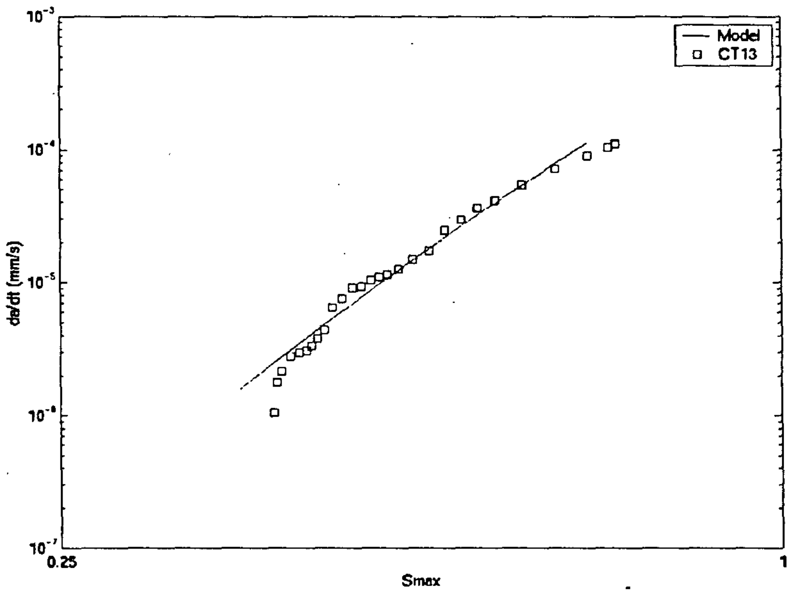

FIGURE 3. Identification of the pure creep model at 650°C

To complete the information obtained by tests, all the phenomena concerning the crack opening and closure and the stress redistribution at the crack tip induced by plasticity or visco-plasticity during the crack propagation can be obtained by a numerical analysis using a finite element method, as it has been made by Prigent (1) in the case of Astroloy superalloy. This numerical analysis conducts to the identification of $a(T)$ and $\omega(T)$ threshold relaxation parameters of equation 9 (the visco-plastic behaviour of the material at high temperature is of course supposed to be known and predicted by accurate constitutive models).

The oxidation kinetics of the material as well as its temperature dependency is (α_o and Q_o coefficients of equation 6) supposed to be known. The evolution of the material toughness ahead of the crack tip (K_{cox}^o and then the ratio $\frac{K_{cox}^o}{K_{cv}^o}$; mz^* and u coefficients of equation 4) can be deduced from special tests performed on oxidised specimens. The coefficient c (equation 7) which traduces the loading effect on the oxidation kinetics is identified by one test result obtained in fatigue-creep regime, for instance by the simulation of a test with hold time.

3.2 Predictions of isothermal tests

We give in this section several comparisons model/prediction of tests performed on specimens with notches of different geometry (KB, KBR and FC).

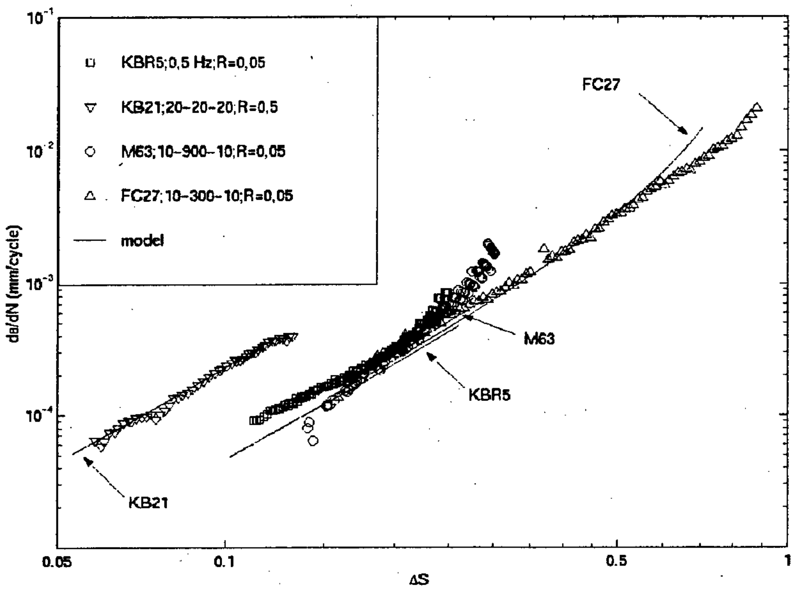

FIGURE 4. Prediction of time and load ratio effects at 550°C

In figure 4 are reported the model predictions at 550°C. As it can be seen, the model predicts almost any time effect at this temperature in agreement with the tests results. The load ratio effect is also correctly reproduced. Complex loading have been defined to simulate on a specimen what can be observed on the real component such as SF1, SF2 and A'20 cycles reported on figure 5.

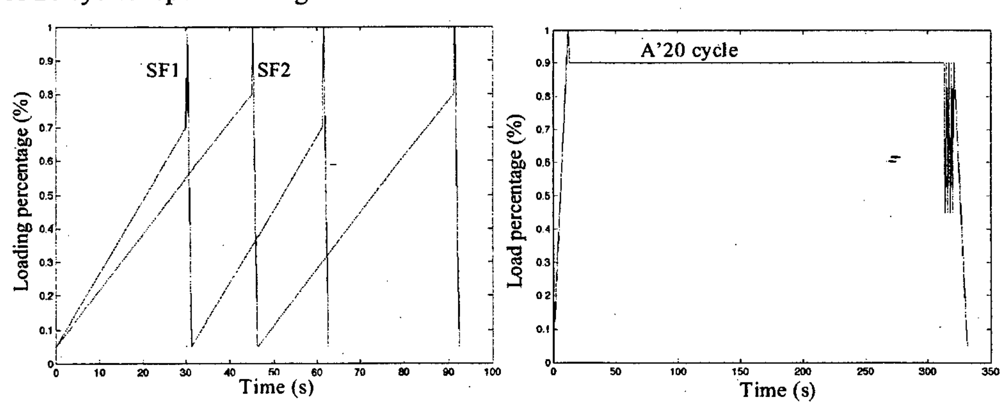

FIGURE 5. Complex cycles SF1, SF2 and A'20

The figure 6 gives the model predictions for these complex cycles. The loading rate effect is well reproduced as SF1 and SF2 cycles are concerned. The test reproducing A'20 mission is predicted with a little too high crack propagation rate.

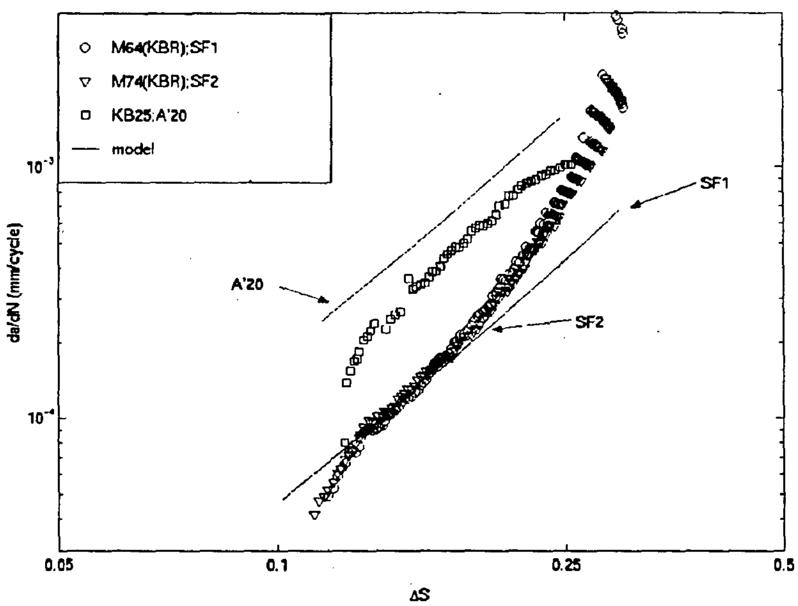

FIGURE 6. Predictions of complex tests SF1, SF2 and A'20 at 550°C

We present now tests predictions at 650°C for which time effects are important.

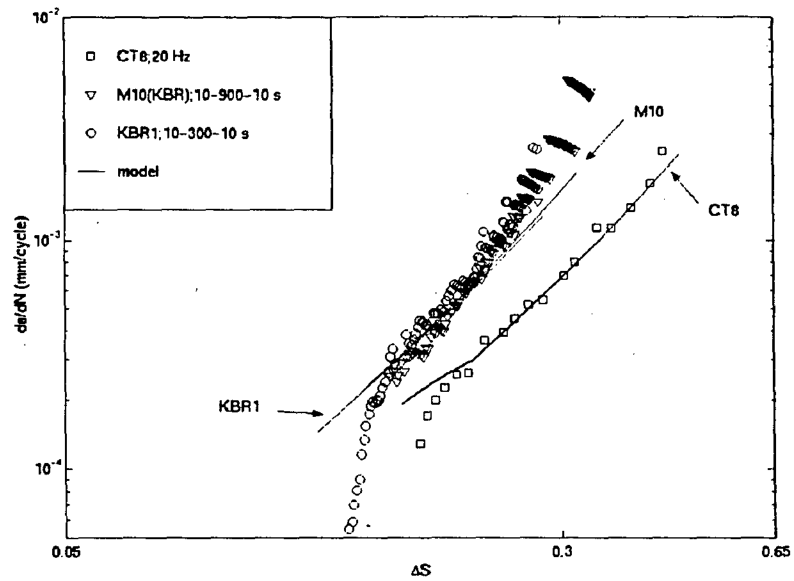

FIGURE 7. Predictions of tests with hold time at 650°C

In figure 7 are given the predicted curves for tests with different hold times. The model predictions are quite good whatever the hold time duration. It appears a small difference between the two predicted tests with hold times of 300 s and 900 s, in agreement with the tests results.

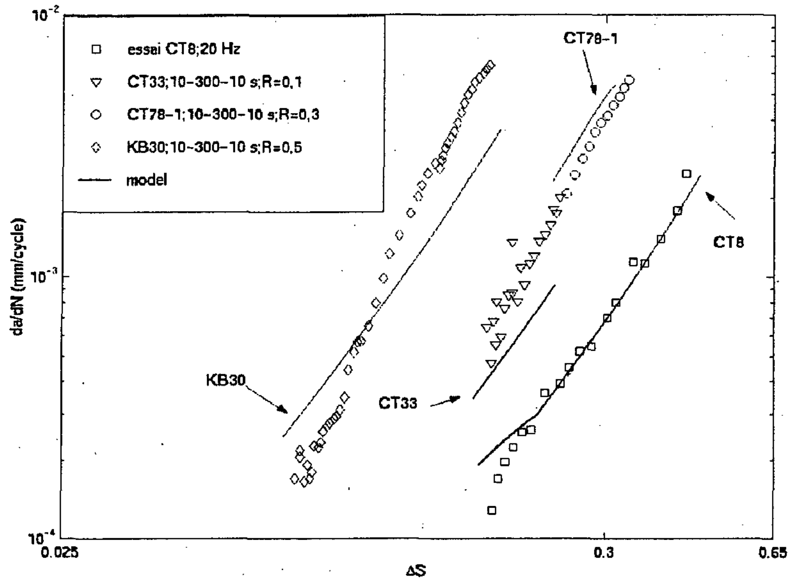

FIGURE 8. Predictions of tests with hold time for different load ratios at 650°C

The last predictions reported on figure 8 concern the loading ratio effects at 650°C for tests with the same hold time of 300 s. The loading ratio effects predicted by this crack propagation model reproduce quite correctly what it can be observed with N18 superalloy and for tests with consequent creep-fatigue-oxidation interaction.

3.3 Predictions of complex tests under non isothermal condition

Three different complex loading in non isothermal condition were studied [8] to simulate on specimens what can be subjected to critical zones of a turbine disc.

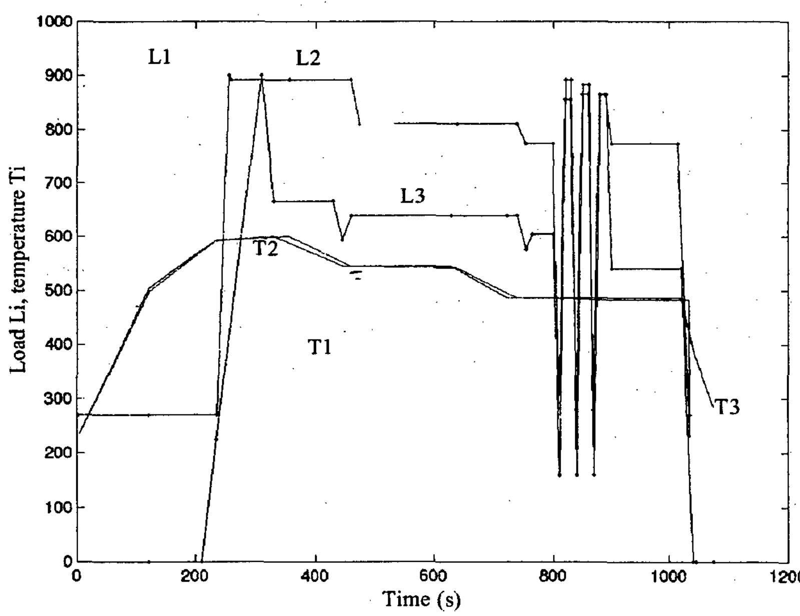

FIGURE 9. Thermo-mechanical fatigue cycles simulated in the laboratory

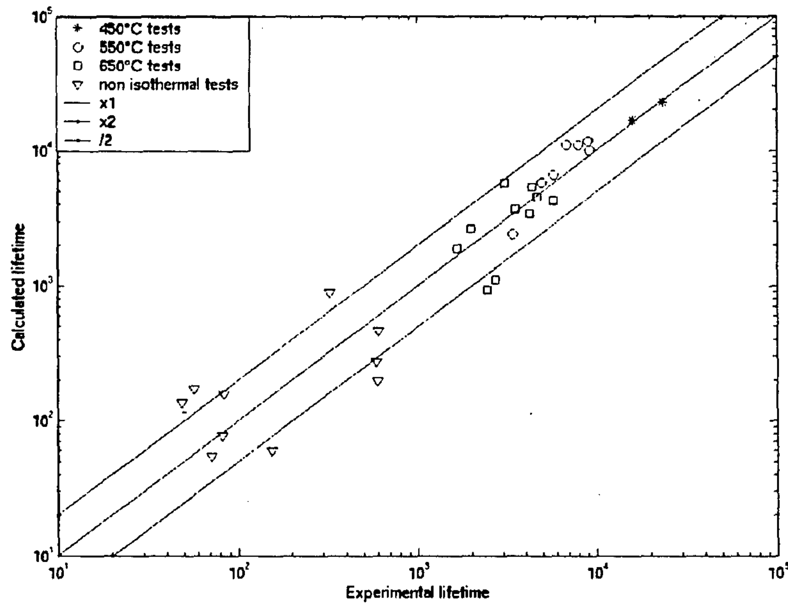

FIGURE 10. Comparisons between calculated and experimental lifetimes

The applied load to the specimen and the temperature loading are reported in figure 9. The temperature varies for each cycle from about 200°C to 600°C. The lifetime is the number of missions to reach a given crack length. We present in figure 10 the comparisons between the experimental and calculated lifetimes for isothermal and non isothermal tests. The model predictions are fairly good, as well as for many isothermal tests at several temperatures and loading conditions, and for the thermo-mechanical fatigue tests for which the lifetime is correctly predicted, even if the model parameters have not been identified at the maximum temperature of the cycles (600°C) but interpolated with results obtained at 550°C and 650°C.

4 CONCLUSION

The works summarised in this paper demonstrate actual possibilities to predict the crack propagation of metallic materials at high temperature such as Ni-base superalloy for turbine discs. The strong requirements in design procedures have led to the development of sophisticated crack propagation models to account for fatigue, creep and environment effects as well as theirs interactions on crack propagation rate. We proposed a phenomenological fatigue-creep-oxidation interaction model for an application in isothermal condition but also in non isothermal condition. We presented the lifetime prediction of many isothermal tests and of a few anisothermal tests. Predictions are fairly good for the set of experimental data and are very promising to make the model predictive under complex thermo-mechanical loading.

Acknowledgements

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